An evaluation of wetland assessment techniques and their applications to decision making

MA Thiesing

US Environmental Protection Agency, Region II, 24th Floor, 290 Broadway, New York, New York 10007-1866 USA

Abstract

In the United States, wetland assessment, or the evaluation of the ecological condition and/or function of wetlands, most frequently occurs when those wetlands are proposed to be either impacted or lost as a result of development. The need to consider ecological value and function in the decision making process has led to the development of a wide variety of techniques for wetland assessment. The earliest techniques which were developed were considered to be rapid assessment procedures, which are most often used to evaluate single sites and to provide project-specific analyses. Some rapid assessment procedures, such as the Wetland Evaluation Technique (WET), which was developed by the US Army Corps of Engineers, considered broad groups of functions which included fish and wildlife habitat value, but also included flood control, groundwater recharge/discharge and value of the site for recreation and education. All of these techniques, however, are limited in their application. Most involve either qualitative results with little predictive value, or include subjective considerations based on best professional judgement. More recent techniques, such as the Hydrogeomorphic Method for Wetland Assessment (HGM) are based on peer-reviewed mechanistic models which are data-based, but which are difficult to apply and consider.

All of the methods evaluated ignored macro-scale, landscape and system-level functions, which are critical for cumulative impacts assessment and for the conservation of biodiversity. More recent assessment efforts are being driven by efforts to protect watersheds as a whole, rather than the specific sites within these watersheds. As a result, more current assessment techniques evaluate populations of wetlands against identified reference wetlands in that landscape, which allows more objective comparisons of functional performance. This paper examines the most commonly used wetland assessment procedures and compares their uses for resource management, restoration and landscape-level conservation.

Keywords: wetland assessment, rapid assessment, hydrogeomorphic method, landscape-level assessment, bioindicators

Introduction

In the past thirty years, there has been an increased public awareness of the values and benefits of wetlands to society. In the United States, this has produced changes in national policy, which include increased regulation of wetlands as well as both public and private conservation efforts to protect, acquire, enhance and restore these resources. At the same time, wetland areas are under increasing pressure from development and urbanisation within watersheds. Both resource management concerns, as well as regulatory needs, often force choices among the different, sometimes conflicting uses. The need to make decisions about wetlands has thus created a need for information on the value, both from an ecological and a societal standpoint, of these wetland resources; hence the need for wetland assessment. This paper uses examples from the United States to examine methods which are currently available for wetland assessment, evaluates their applications and shortcomings, and provides recommendations for approaches to wetland assessment based on the information needs and goals identified.

In the United States, the US Congress directed the US Fish and Wildlife Service (USFWS) in 1986 to develop a nationwide inventory of wetlands, in order to provide information to the public and to the government on the location and types of wetlands in the US. This National Wetlands Inventory (NWI), which is approximately 89% complete (USFWS 1998) has identified the location of wetlands in the US using stereoscopic pairs of infrared photographs. Fieldwork is then performed to confirm, or 'ground-truth' photographic data and collect additional data, from which the wetlands are ultimately mapped. The inventory further classifies wetlands by type based on substrate or soil type, dominant hydrologic regime, vegetation community and aquatic habitat type, among other things (USFWS 1998). NWI maps are not intended to provide wetland boundaries for regulatory purposes, but rather to provide information to the public about the possible locations and types of wetlands in a given geographic area. Information arising from the National Wetlands Inventory indicates that the United States has lost over half of the wetlands which historically existed in the lower 48 states, most frequently as a result of drainage for agriculture (Dahl 1990).

The development of inventory data is a type of assessment: it provides information identifying the locations, areal extent and types of wetlands existing within a landscape. The term assessment, however, as it is most commonly used, implies a more detailed evaluation of how a specific wetland or range of wetlands functions. Assessment may also involve an evaluation of the condition, or ecological integrity, of the wetland system.

In discussing wetland assessment, we often speak in terms of wetland functions and wetland values. Wetland functions are defined as physical, chemical, or biological processes occurring within wetland systems. Wetland values are attributes of wetlands which are perceived as valuable to society. Wetland functions are therefore able to be more objectively assessed or measured, while wetland values are inherently subjective and may be difficult to assess. Nevertheless, decision making is a valuative process and consequently must consider wetland values in weighing decision alternatives and consequences. Consideration of wetland value is often indirectly imbedded in the assessment process as well, because the choice of which functions to assess is often made based on the perception of which wetland functions are most important.

There are a wide variety of applications for which information on wetland function and condition may be used. The most common uses of assessment to date have been: 1) The evaluation of wetlands proposed for fill for development; 2) Evaluation of impacts for planning purposes; 3) Evaluation of wetland restoration potential for conservation programs; 4) Determining wildlife habitat potential for properties proposed for acquisition for wildlife management purposes, or where changes in land management are proposed to occur.

The commonest use of wetland assessment to date has been for the evaluation of impacts to wetlands from development. The placement of fill material into wetlands and other waters, which results in wetland loss, is regulated by §404 of the Clean Water Act and requires a permit from the US Army Corps of Engineers. The §404 regulations direct that, for a permit to be granted, it must be demonstrated that the placement of fill is unavoidable and that it has been minimised to the maximum extent possible. If these criteria have been met, the permit applicant must mitigate for any unavoidable impacts that the fill may have on the aquatic ecosystem. This typically involves some form of wetland creation, enhancement, or restoration within the affected ecosystem; its purpose is to compensate for wetland value lost to the system as a result of fill. In order to objectively determine whether wetland loss can be compensated by mitigation, the functions performed by the wetland proposed to be impacted must be determined. An additional policy directive within the wetland regulatory program proposes that there should be no net loss of wetland functions and values. This has augmented the need for an objective protocol to assess wetland functions, so that not only the feasibility, but also appropriate amounts and types of compensatory mitigation may be determined when wetlands are proposed to be impacted and/or lost. These regulatory imperatives may indirectly guide planning processes as well, since the evaluation of plan alternatives must consider future permit requirements for each alternative evaluated.

In response to the desire to achieve the goal of no net loss of wetland function, there have been over forty different methods developed in the last decade alone which are designed to assess wetlands (Bartoldus 1999). They range in level of rigor from those based on *ad hoc* consensus among professionals to more sophisticated peer-reviewed mechanistic models. Consequently, these techniques differ greatly in the level of detail, objectivity and repeatability of the results. There is also considerable variability in the range of wetland functions that are considered by any given technique. Some methodologies are narrowly focused and may only consider a single or a small related group of functions such as fish habitat, bird habitat, wildlife habitat, flood storage, etc (Bovee & Milhous 1978, US Fish and Wildlife Service 1980, Heinemann 1981, Morris & Bowden 1986, Cable et al 1989, Whitlock et al 1995); others look at a broader range of wetlands functions concurrently, such as flood storage capacity, sediment stabilisation, nutrient uptake, primary production export and fish and wildlife habitat (Larson 1976, Adamus 1983, Hollands & Magee 1985, Adamus et al 1987, Abbruzzese et al 1990, Amman & Stone 1991, Bartoldus et al 1992, US Army Corps of Engineers 1993, 1995, Bartoldus et al 1994, Ruby et al 1995, Miller & Gunslaus 1997). Some of these techniques have components to consider wetland values as well as functions. Because wetlands are such complex systems, however, there is no single technique, no matter how comprehensive, which can evaluate all functions performed by a given wetland.

Generally speaking, assessment methods fall into approximately four general types of approaches:

1 *Inventory and classification*. These are objective techniques which describe the areal extent and/or types of wetlands within a given landscape. This includes such information as the National Wetland Inventory maps, watershed-based GIS data, and remote sensing data.

2 *Rapid Assessment Protocols*. These are mostly low-cost techniques in which the data necessary to perform the assessment may be gathered in a short period of time. Rapid assessment protocols tend to focus mostly on single wetlands or small populations of wetlands. The results are likely to be either completely qualitative, or involve a large extent of subjective ('best professional judgement') information.

3 *Data-driven Assessment Methods*. These are usually expensive to develop, often model-based, but provide a high degree of reproducibility. The results often have predictive value.

4 *Bioindicators/Indices of Biotic Integrity.* These techniques involve a selected set of variables, which are measured across wetland types. The variables may be evaluated separately, or used to develop multimetric indices, which can be used to measure the condition or ecological integrity of a wetland and can be used as environmental triggers to identify long-term changes. They do not provide a reliable assessment of functional capacity.

Some of the methodologies may incorporate elements of more than one type of approach.

Rapid assessment methodologies have been and continue to be the most commonly used methodologies. One of the most widely used of the multi-function rapid assessment methods is known as the Wetland Evaluation Technique or WET 2.0 (Adamus et al 1987, Adamus et al 1991). This technique was developed through the US Army Corps of Engineers for use in making wetland permit decisions. WET is a broad-brush tool, which uses the presence or absence of a large set of wetland characteristics as correlative predictors of wetland functions. It is not designed to provide quantitative measurements of functional performance; rather, it is designed to predict the *qualitative likelihood* (high, medium or low) that a wetland performs given functions, to an unspecified degree. These functions include groundwater recharge, groundwater discharge, floodflow alteration, sediment stabilisation, sediment/toxicant retention, nutrient removal/transformation, aquatic diversity and abundance, wildlife diversity and abundance, recreation, and uniqueness/natural heritage, as well as species-specific fish and wildlife habitat assessments. For most of these functions, the protocol evaluates both the effectiveness, or the ability of the wetland to perform the function based on its structure, as well as the opportunity that the wetland has to perform the function. The relationships between characteristics and functions which WET uses are well-supported in the scientific literature and the rationale for WET is exceptionally well documented (Adamus et al 1991). WET was originally developed for the US Federal Highway Administration (Adamus 1983), and was used to do a 'broad brush' evaluation of relative impacts to wetlands for different highway location alternatives. It provides an excellent procedure for rapid screening of different alternatives which would affect wetlands in a landscape, and looks at a broad array of wetland functions. It is not, however, suitable for assessing the actual extent of wetlands impacts, or the type, location, or amount of mitigation that would be necessary to compensate for functions lost due to impacts. Furthermore, some of the predictors used in WET, particularly with respect to fish and wildlife habitat, differ in different regions of the US, and so do not always accurately predict habitat use likelihoods. Finally, while the results summary is fairly simple, the decision trees used to reach those results are quite complex, which tends to make the rationale for the end results somewhat obscure.

In contrast, a less complex, consensus-based assessment method known simply as the Highway Methodology has been used to assess wetlands in connection with planning and permitting of highway projects in the New England region of the US (US Army Corps of Engineers 1993, 1995). This method also does not yield quantitative results; however, it documents the rationale for the assessment results in a manner that is completely transparent. It also includes components which assess whether a wetland is likely to provide selected wetland values. While this method is not suitable for providing evaluation of losses for determining compensation ratios, it is simpler to use than WET and was designed for the region in which it is being used, so that it may be more sensitive to region specific wildlife habitat potential.

Another commonly used protocol for rapid assessment, which is used to evaluate fish and wildlife habitat within a given ecological community was developed by the US Fish and Wildlife Service (1980). This method, known as the Habitat Evaluation Procedure (HEP), uses a consensus-based field evaluation based on species-specific conceptual models for habitat use. HEP was originally developed for the evaluation of wildlife habitat potential for lands being considered for acquisition for wildlife management purposes. It provides a semi-quantitative measure of the number of habitat units per acre that a community can provide for each species evaluated. Because HEP can assess habitat value for a planned future condition as well as existing conditions in a given community, it has been used to assess the value gained from compensatory mitigation. The species models used in HEP are conceptual, based on ecological characteristics of the species which have been reported in the literature. HEP also allows for modifications to the models to better reflect regional differences in the habitat use of the species. Unfortunately, the procedure is easily affected by bias on the part of the field evaluators, both in terms of which species are selected for evaluation and in terms of the weights assigned to the habitat features. The relative ease with which the evaluation may be biased requires a greater degree of scrutiny in the weighing of results in the decision-making process.

Each of these rapid assessment techniques has limitations to their use. The data input for WET is more objective, and involves much less subjective judgement on the part of the evaluators. However, the results of WET cannot be used to compare the degree of functional performance of a wetland to any other wetland within a system, because there is no measure of function, only a prediction about whether that function may be performed. Both HEP and the Highway Methodology assess wetlands by using a consensus process; this means that the results are subjective, are not likely to be reproducible, and may be severely biased if the evaluators lack sufficient background to perform the assessment. This inherent subjectivity means that the results of such assessments cannot be reliably compared across large populations of wetlands or for the same wetlands over time, because the evaluative process is not directly reproducible.

The recognition that greater objectivity as well as reproducibility in wetland assessment was needed has led to reliance in certain decision making processes on more data-based analytical methods. Most such methods tend to be limited to single wetland functions; for example, HEC models (Hydrologic Engineering Center, US Army Corps of Engineers 1988) are techniques used for quantifying the hydrologic impacts of a project on a site and on the surrounding area, in order to evaluate flooding risks from development. Because these methods are data-intensive and often involve the use of a model, they are usually expensive and time consuming to perform; however, the outputs have good predictive value and reliability across wetland types. The narrow focus of these techniques limits their applicability to special problems and does little to address the need for objective information about a wide variety of wetland functions.

The decisions made by the §404 Regulatory program increasingly require not only some means of quantifying functional performance, but also need to address a wide variety of wetland functions. Brinson (1993) began to address this need with the development of the Hydrogeomorphic Classification Method (HGM), which has since evolved into a technique (Smith et al 1995) which can be used to measure a large suite of wetland functions in a quantifiable, consistent manner across a large geographic region. HGM is a reference-based technique, which develops a model for measuring wetland functions based on wetlands which are established as standards within that landscape. First, the wetlands are classified by hydrology and geomorphic setting into subclasses. The assessment protocol is then established by measuring functions across a set of wetlands of the same hydrogeomorphic subclass within a geographic region (called the reference domain) to determine the range of performance, for those functions in wetlands within the landscape. These functional profiles are used to develop functional indices, which estimate the capacity of a wetland to perform a function relative to other wetlands of the same hydrogeomorphic type in the reference domain. These are based on reference standards, which are defined as the conditions under which the highest *sustainable* level of function is achieved across the suite of functions performed by wetlands of that subclass. The protocol is developed by a designated team of experts and is subjected to both peer review and public comment before the model is finalised. Thus, HGM provides an objective means by which functional performance can be measured, objectively compared across geographic areas and evaluated.

The Corps of Engineers proposed a National Action Plan for the adoption of HGM as the national standard for wetland assessment for use within the regulatory program (US Army Corps of Engineers 1996), which stated that the goal would be to develop sufficient models over the subsequent two years so that HGM could be used in 80% of the permit cases. As of this date, there are not sufficient models to apply HGM as an assessment method in most parts of the US, nor is the protocol for its use sufficiently documented to allow the development of consistent functional models.

HGM has a number of fundamental strengths which set it apart from other assessment techniques. Perhaps its greatest strength is that model development is an iterative process, which allows for refinement and validation based on data and expert review. As an approach, HGM is both objective and quantitative. It uses reference wetlands to provide objective bases for standards of comparison — something which is clearly missing from almost all other assessment techniques. Once the model is developed, the assessment of a specific wetland would be expected to be relatively rapid, consistent, and reproducible. However, the cost of model development is high and the results of the assessment and the functions measured are both complex and rather obscure, and may not capture functions of importance as defined by established management objectives. Finally, HGM does not adequately evaluate highly impacted wetlands such as those wetlands in urban settings. Reference standards are based on the highest *sustainable* level of functional performance. Owing to their location within the landscape, urban wetlands may be performing functions (eg sediment removal) at a level higher than the reference standard and would have a significant benefit to the watershed because of their location within it. The application of HGM would result in a low functional rating for such a wetland because both positive and negative deviations from the reference standard are set lower than the standard. Such performance is not likely to be sustainable in the long term but nonetheless results in much greater benefits. Unfortunately, wetlands which receive low functional indices do not receive the same priority for protection as those which would receive high functional indices; as such, they may be at greater risk of destruction. This challenge is currently being worked on by the US Army Corps of Engineers Waterways Experiment Station.

A data-based approach which also evaluates wetlands across large geographic landscapes is the development and use of Bioindicators, or Indices of Biotic Integrity (IBIs). This type of approach was developed to rapidly evaluate the condition of streams and open waters (Yoder 1991a,b, Davis et al 1996, Karr & Chu 1997), and has only recently been evaluated as an approach to evaluating wetland conditions. The intent of each of these techniques is not to evaluate an entire suite of functions, but rather to pinpoint those which are characteristic of a specific set of environmental conditions, and to use their presence as indicators of condition and over time, as indicators of ongoing impacts. Species which are sensitive to degradation, for example, would act as indicators of high quality environmental condition. The loss of such species would be an indication that change is occurring and being triggered by environmental degradation. Karr and Chu (1997) indicate that careful program design can result in indicators that are both biologically useful and statistically robust. These techniques do not measure or evaluate functional capacity; however, the use of bioindicators and IBIs offer a promising approach where the goal of assessment is not assessing functional capacity but rather ecological condition of a wetland. As our focus in wetland protection becomes based more on watershed management, the measurement of condition assumes increased importance. It takes considerable time and data to develop a reliable suite of indicators; however, it is not necessary to evaluate many different functions, so development of bioindicators and IBIs is likely to be less costly than the development of HGM models.

Rapid assessment protocols evaluate individual wetlands; models such as HGM and IBIs provide assessment of wetlands in context of the geographic landscape. The evaluation of landscapes can be performed using GIS (Johnston et al 1988). The only assessment approach that addresses evaluation of wetlands at the landscape level is called the Synoptic Approach to Wetland Designation (Leibowitz et al 1992) and has been used in a few cases in the northwestern United States (Abbruzese et al 1990). This approach ranks watersheds using landscape level data such as GIS-based maps to evaluate watersheds for a variety of functions in terms of their capacity and sensitivity to wetland loss. It has not been used widely and its drawbacks are not fully evident; however, it can offer a useful approach for the evaluation of cumulative impacts.

Each of these approaches evaluates wetland functions differently; however, assessment methodologies do not exist at all for the evaluation of larger, landscape level effects. At the landscape level, wetlands interact with one another; they provide refugia for wetland animals within the landscape and seed banks for wetland vegetation; they are able to serve as sources for species dispersal and migration to other wetlands within the landscape. They provide support for migratory species. In addition, in areas such as urban settings where wetlands are scarce in the landscape, their relative contributions to habitat support, regional biodiversity and watershed-wide hydrologic functions assumes a disproportionate importance. Most landscape approaches emphasise wetland size and contiguousness as being significant from a landscape perspective. The contributions of large wetlands to biodiversity has been previously documented, and certainly continuity across a landscape is important for migratory support. However, a simulation study by Gibbs (1993) found that the loss of small wetlands (less than one acre in size) from a landscape resulted in significant regional extinction rates for some bird and many amphibian species because the interwetland distance became too great to allow outward migration of displaced individuals. Consequently, the role of small wetlands in contributing to regional biodiversity at the landscape level may have been underestimated. The maintenance and support of biodiversity may be one of the most critical landscape level effects which has been left largely unassessed in any systematic way.

Not every decision making process requires the same level of information. Qualitative information may be perfectly adequate if the only consideration is to screen alternatives for feasibility. On the other hand, when unique, rare, or regionally/globally significant wetlands are at serious risk of loss or damage, detailed data may be necessary to evaluate the impacts of present or proposed damage. In addition, little attention has been given toward the development of reliable techniques to assess cumulative impacts to wetlands. As we move toward a greater emphasis on comprehensive, watershed-based protection, this becomes even more important in planning for sustainable uses of these resources.

Toward that end, I offer the following recommendations for improving the way that we incorporate wetland assessment into our decision-making processes:

1 At the outset of the decision making process, clear goals for both immediate and long-term management of wetlands must be established. The level and focus of the information needs for assessment purposes cannot otherwise be determined.

2 There needs to be a clear understanding by the decision maker of what the chosen methodology will not provide, as well as what it will. The choice of what to leave out of the assessment must be able to be addressed within the scope of the decision.

3 Reference sites should be established regardless of whether any technique is systematically adopted by resource managers. Reference sites provide objective standards for both the measurement of functional capacity, even in assessment methods which rely on best professional judgement and consensus. They also provide reality-based targets for wetland restoration efforts and allow for long-term monitoring of wetland dynamics within the landscape. The most useful sites would be those which are under public ownership and/or long-term management, such as long-term ecological research sites, since these are most likely to be protected.

4 Techniques for the systematic effects of landscape-level effects, particularly the relative contributions of wetlands to regional biodiversity, need to be established. Without such protocols, we will be unable to realistically evaluate cumulative impacts of actions involved in our decisions.

5 Inventory data should be collected wherever possible if biodiversity is to be considered realistically in decisions. The increased availability and decreasing costs of GIS systems makes management of such information simpler. Partnerships between resource managers and non-governmental groups, academia and the public could be productive means of increasing the availability of these data.

6 Finally, we need to realise that there is no 'magic bullet' when it comes to objective assessment. The choice of methods is often dictated strictly by the available resources; however, a tiered approach, which could incorporate rapid assessment to screen alternatives and perhaps incorporate a more detailed approach for analysis of a preferred option, could provide a way to maximise the value of the information.

Note: The information presented in this paper has not been submitted to the US Environmental Protection Agency for the agency peer review process. All opinions and recommendations expressed herein are those of the author and do not necessarily represent the opinions or policy of the USEPA.

References

Abbruzzese B, Leibowitz SG & Sumner R 1990. *Application of the synoptic approach to wetland designation: A case study approach*. EPA/600/3-90/072, USEPA Environmental Research Lab, Corvallis, OR.

Adamus PR 1983. *A method for wetland functional assessment; Vol. II, FHWA assessment method*. US Dept. Trans., Fed. Highway Admin. Rep. No. FHWA-IP-82024.

Adamus PR, Clairain jr EJ, Smith RD & Young RE 1987. *Wetland evaluation technique (WET); Vol. II, Methodology (Operational Draft Report)*. Environmental Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Adamus PR, Stockwell LT, Clairain jr EJ, Morrow ME, Rozas LP & Smith RD 1991. *Wetland evaluation technique (WET); Vol. I, Literature review and evaluation rationale.* Environmental Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Amman AP & Stone AL 1991. *Method for the comparative evaluation of nontidal wetlands in New Hampshire.* New Hampshire Department of Environmental Service. Concord, NH NHDES-WRD-1991-3.

Bartoldus CC, Garbisch EW & Kraus ML 1992. *Operational draft. Wetland Replacement Evaluation Procedure (WREP)* Environmental Concern, St. Michaels, MD.

Bartoldus CC, Garbisch EW & Kraus ML 1994. *Evaluation for planned wetlands (EPW).* Environmental Concern, St. Michaels, MD.

Bartoldus CC 1999 (in press). A comprehensive review of wetland assessment procedures: A guide for wetland practitioners. Environmental Concern, St. Michaels, MD.

Bovee KD & Milhous R 1978. Hydraulic simulation in instream flow studies theory and techniques. Cooperative Instream Flow Service Group. Ford Collins, Colorado. Paper 5, FWS/OBS-78/33.

Brinson MM 1993. A hydrogeomorphic classification for wetlands. Wetlands Research Program TR-WRP-DE-4. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cable T, Brack jr TV & Holmes VR 1989. Simplified method for wetland assessment. *Environmental Management* 13, 207–213.

Dahl TE 1990. *Wetlands losses in the United States 1780s to 1980s*. US Department of the Interior, Fish and Wildlife Service, Washington DC.

Davis WS, Snyder BD, Stribling JB & Stoughton C 1996. Summary of state biological assessment programs for streams and rivers. EPA 230-R-96-007. Office of Policy, Planning and Evaluation, US Environmental Protection Agency, Washington DC.

Gibbs JP 1993. Importance of small wetlands for the persistence of local populations of wetland-associated animals. *Wetlands* 13 (1), 25–31.

Heinemann HG 1981. A new sediment trap efficiency curve for small reservoirs. *Water Resour. Bull. Am. Res. Assoc.* 17, 825–830.

Hollands GG & Magee DW 1985. A method for assessing the functions of wetlands. In *Proceedings of the National Wetland Assessment Symposium (1985)* eds J Kusler & P Riexinger, Association of State Wetland Managers, Berne, NY.

Johnston CA, Detenbeck NE, Bonde JB & Niemi G 1988. Geographic Information Systems for cumulative impact assessment. *Photogrammetric Engineering and Remote Sensing* 54(11), 1609–1615.

Karr JR & Chu EW 1997. *Biological monitoring and assessment: Using multimetric indices effectively*. EPA 235-R97-001. University of Washington, Seattle.

Larson JS (ed) 1976. *Models for assessment of freshwater wetlands*. Publication No 32, Water Resources Research Center, University of Massachusetts, Amherst, MA.

Leibowitz SJ, Abbruzzese B, Adamus PR, Hughes LE & Irish JT 1992. *A synoptic approach to cumulative impact assessment: A proposed methodology*. US Environmental Protection Agency, Corvallis, Oregon. EPA/600/R-92/167.

Miller RE jr & Gunslaus BE 1997. *Wetland Rapid Assessment Procedure (WRAP)*, South Florida Water Management District Technical Publication REG-001.

Morris JT & Bowden WB 1986. A mechanistic, numerical model of sedimentation, mineralisation, and the decomposition for marsh sediments. *Soil Sci. Am. J.* 50, 96–105.

Reppert RT, Sigleo W, Stachiv E, Messman L & Meyers C 1979. *Wetland values: Concepts and methods for wetlands evaluation.* 1WR Res. Rep. 79-R-1, US Army Corps of Engineers, Fort Belvoir, VA.

Ruby T, Cesanek WE & Miller KE 1995. Estimating relative wetland values for regional planning. *Wetlands* 15(2), 93–107.

Smith RD, Ammann A, Bartoldus C & Brinson MM 1995. *An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands and functional indices*. US Army Engineer Waterways Experiment Station, Wetlands Research Program Technical Report WRP DE-9,Vicksburg, MS.

US Army Corps of Engineers 1993. *The Highway Methodology Workbook*. US Army Corps of Engineers New England Division. NEDEP-360-1-30.

US Army Corps of Engineers 1995. *The Highway Methodology Workbook Supplement*. *Wetland functions and value: A descriptive approach.* US Army Corps of Engineers New England Division. NEDEP-360-1-30a.

US Army Corps of Engineers 1996. National action plan to develop the hydrogeomorphic approach for assessing wetland functions. *Federal Register* 61, 160, 42593–42603.

US Fish and Wildlife Service 1980. *Habitat Evaluation Procedures (HEP)*. Ecological Services Manual 101, US Fish and Wildlife Service, Washington DC.

Whitlock AL, Jarman N, Medina JA & Larson J 1995. *WETHINGS*. The Environmental Institute, University of Massachusetts.

Yoder CO 1991a. Answering some questions about biological criteria based on experiences in Ohio. In *Water Quality Standards for the 21st Century*. Office of Water, US Environmental Protection Agency, Washington DC, 95–104.

Yoder CO 1991b. The integrated biosurvey as a tool for evaluation of aquatic life use attainment and impairment in Ohio surface waters. In *Biological criteria: Research and regulation.* EPA-440-5-91-005. Office of Water, US Environmental Protection Agency, Washington DC, 110–122.